Energy Use and Savings Potential for Laboratory Fume Hoods

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Abstract

Typically relied upon as the primary source of ventilation in laboratory-type facilities, while also providing for safe conditions in areas in which experiments are being conducted, fume hoods are critical energy end-use devices. Fume hoods require large amounts of airflow, which drives the overall HVAC sizing and energy requirements of the buildings in which they are located. Per-hood energy costs range from $4,200 for moderate climates such as Seattle, USA to $8,200/year for extreme cooling climates such as Singapore. With an estimated 750,000 hoods in use in the U.S., the aggregate energy use and savings potential is significant. We estimate the annual operating cost of U.S. fume hoods at approximately $3.8 billion, with a corresponding peak electrical demand of 5,000 megawatts. With emerging technologies, per-hood savings of 50-75% can be safely and cost-effectively achieved.

Introduction

Efforts to improve energy efficiency must be responsive to a host of "non-energy" considerations, such as safety. In many cases non-energy benefits can in fact provide an additional impetus for technology innovation beyond the value of direct energy savings (Mills and Rosenfeld 1996; Pye and McKane 1999; Worrell et al. 2003). This is the case with laboratory fume hoods.

Laboratory fume hoods have long been used to protect workers from breathing harmful gases and particles, and are ubiquitous in pharmaceutical and biotechnology facilities, industrial shops, medical testing labs, private and university research labs, and high school chemistry labs. Fume hoods are box-like structures, often mounted at tabletop level with a movable window-like front called a sash. They capture, contain and exhaust airborne hazardous materials, drawn out of the hood by fans through a port at the top of the hood. Their fundamental design has gone largely unchanged for the past 60 years (Saunders 1993).

As depicted in the Figure 1, overall fume hood energy use is the product of a number of sub-systems, including: supply and exhaust fans, space-cooling energy, space-heating energy, and (in some cases) humidification or de-humidification and terminal reheat. We developed an engineering spreadsheet model to perform baseline analysis and test the per-hood and national impacts of energy efficiency improvements.

Highlighting the "systems nature" of fume hood design and application, hoods require large amounts of airflow that tend to drive the size, and first cost of central heating, ventilating and air-conditioning (HVAC) systems in buildings where hoods are located. As a result, fume hoods are a major factor in making a typical laboratory four- to five-times more energy intensive than typical commercial buildings (Bell et al. 2002). A typical hood consumes 3.5-times more energy than an average house. With 0.5 to 1.5 million hoods in use in the U.S. ("central" estimate 750,000), aggregate energy use and savings potential is significant. As will be described below, the annual operating cost of U.S. fume hoods is $3.8 billion, with a corresponding electricity use of 28 TWh, peak electrical demand of 5,000 megawatts and 0.2 Exajoules (191 TBTU) of heating fuel.

Further amplifying the need to improve fume hood design, recent research shows that increasing the amount and rate of airflow (and, consequently, energy use) does not tend to improve containment. Instead, errant eddy currents and vortexes can be induced around hood users as airflows around workers and into the hood, reducing containment effectiveness and compromising safety (Bell et al. 2002).

Baseline Energy Use and Analysis of Potential Savings

We have modeled the potential energy use and savings on a per-hood basis across a variety of weather locations around the globe (Table 1). Total energy costs are more sensitive to the cooling climate (which contributes up to \$5000 to the total for the countries analyzed) than to the heating climate (which up to \$2500/year to the total). Our calculations account for the heating, cooling, and movement of fume hood air. Depending on climate, estimated costs range from \$140 to \$ 250/m3-minute (\$4 to \$7/cfm). For one country (the United States) we estimate the overall market size, aggregate energy use, and savings potential.

We assume the hood has a 2-meter (6-foot) nominal opening (this is the most common size), and HVAC efficiencies of 1 kW/ton (cooling) and 70% (heating). Overall fan power (supply plus exhaust) is estimated at 64 W/m3-min (1.8 W/cfm) (Weale et al. 2002). For regional analyses, we use factors from Kjelgaard (2001) to determine the space-conditioning loads. As an illustration of the importance of local climate variations, in the case of California annual energy costs vary by approximately $1000/hood-year depending on local climate (Figure 2). Results over a range of climates around the globe are shown in Figures 3 and 4. Cooling is typically the dominant load.

It is important to note that laboratory ventilation is based on 100 percent outside air; thus all the air exhausted by a fume hood has to be made up with unconditioned outside air. Many labs use "reheat." Typically, the outdoor air is initially cooled to 12.7 C (55 degrees Fahrenheit) or lower and then reheated at each zone to the required temperature to maintain the laboratory's set point temperature. Unfortunately, it is possible for only one laboratory zone to actually need maximum cooling. If the outside air is cooler than the supply air set-point then no cooling is required. But, for example, the outside air can be a "perfect" 18.3 C (65 degrees F). In this situation, it is first cooled at the central air handlers and then re-heated back to 65 degrees at many zones. The perverse result of this reheat practice is that in many labs the dominant cooling load is the boiler and the dominant heating load is the chiller. As a result, labs in climates with zero or negligible heating load still use appreciable heating energy. Labs can be designed much better than this, but many are worse than the assumptions used in our calculations. Under the average conditions we specify, reheat results in a load of 3,525 MJ/m^3-minute-year (94,608 BTU/cfm-year). Reheat is typically performed with fuel. Electric reheat is not widespread, but incurs a large energy penalty where used (e.g. nearly twice the fume hood's direct fan energy use in this case for Seattle, Washington in the U.S.).

Approximately 150,000 laboratories populate the United States, with 500,000 to 1,500,000 total fume hoods installed. This range is based in part on interviews of industry experts conducted on behalf of the US Environmental Protection Agency's Labs21 project. The only formally published estimate indicated that there were more than 1 million units in 1989 (Monsen 1989). Our calculations assume a perhaps conservative "central value" of 750,000.

In our analysis of potential savings, we assume an ultimate market penetration in the US of 75% for efficient hood alternatives. Extensive field tests have validated the energy performance of one such design—the "Berkeley Hood--while maintaining or even improving safety containment (Bell et al. 2002). We use national average energy prices as reported by the USDOE Energy Information Administration, as well as state-by-state averages when doing local analyses.

Field trials of state-of-the-art designs have demonstrated pollutant containment down to 34 percent of full flow (Bell et al. 2002). As a conservatism we assume 50% savings in our calculations (note that the theoretical fan savings is a cubed function, which means that a 50% reduction in flow would result in over an 80% savings in fan power). Due to wide variability in local conditions and conventions, we have not included humidity control and exhaust "scrubbing"—used in some hoods—which would increase the total energy savings.

The per-hood and macro-level energy use and savings potential for the US and California is summarized in Table 2. Fume hood energy use will vary with climate, and the associated space conditioning loads. The aggregate U.S. energy savings potential is significant, at approximately $1.4 billion annually, comprised of 11 TWh of cooling and fan energy, 0.08 Exajoules (72 TBTU) of heating fuel, and peak electrical demand of 1,900 megawatts.

Currently Available Energy-Efficient Systems Face Limitations

In the past, four design strategies have been employed to reduce fume hood energy use.

1. Using "auxiliary" (outside) air to reduce energy required by a central HVAC system that conditions the air ultimately exhausted by the hood.

This strategy, referred to as an auxiliary-air hood, introduces outdoor air near the face of the hood just above the worker. Unconditioned air introduced by auxiliary-air hood systems causes uncomfortable conditions for workers during periods of summer and winter temperature or humidity extremes. The auxiliary airflow can also interfere, in various ways, with experiments performed inside the hood. More importantly, turbulence, caused by inflowing auxiliary air at the hood opening, increases the potential for pollutants to spill from the hood towards the worker (Coggan 1997; Feustel et al. 2001). Moreover, auxiliary air hoods only save energy used for conditioning general laboratory air (not for the hood itself). This is the case because the total exhaust flow rate is unchanged. A hood's fan energy consumption is not reduced and may even be increased by the necessity of an auxiliary supply fan. Our estimates indicate that as much as 65 percent of hood electricity is attributable to the fans (moving air) with the balance attributable to conditioning the air.

2. Employing dampers and adjusting fan speed to reduce exhaust airflow through the hood as the sash is closed. This variable air volume (VAV) approach maintains a constant face velocity, enhancing the hood's ability to contain fumes.

This strategy uses dampers, variable speed drives (VSDs), and sophisticated controls to modulate the hood and in the supply and exhaust air streams. These components communicate with direct digital controls (DDC) to provide a variable air volume (VAV) fume hood system. A VAV system establishes a constant face velocity. VAV improves safety, compared to standard hoods, which experience variable face velocity as the face opening is adjusted. Additional controls maintain a constant pressure differential between the laboratory and adjacent spaces. These components and controls add significantly to the system's first cost and complexity and require diligent users. Each hood user must close the sash properly to ensure that the system achieves its full energy savings potential. Also, when sizing air distribution and conditioning equipment, many designers assume worst-case conditions—all sashes fully open—requiring larger ducts, fans, and central plants than would be the case if some sashes are assumed to be partly closed.[2]

[2] Based on the assumption that not all hoods are used simultaneously in a VAV fume hood system, applying a "hood diversity factor" in calculating the building's make-up air has also been suggested as an HVAC energy-saving measure (Moyer and Dungan 1987; Varley 1993).

3. Restricting sash openings by preventing the sash from being fully opened, or using horizontal-sliding sashes that cover part of the hood entryway even when in the "open" position.

This strategy restricts a hood's face opening while maintaining airflow velocity. The face opening is restricted by "stops" limiting vertical sash movement or by using a horizontal sash system that blocks part of the entrance, even when fully open. Stops or sashes are routinely removed by users to facilitate "set-up" of experiments. During set-up, the face velocity is lowered, often significantly, and containment reduced. Users often do not like these restrictions, so it is common to observe hoods under normal use with their stops bypassed or the horizontal sashes removed. In these cases, the air velocity drops below specified levels and compromises safety.

4. Automated designs that promote a vortex in the top of the fume hood, which is maintained by "sensing" whether it is collapsing, and adjusting movable panels in the top of the hood accordingly.

This strategy has been effectively applied to fume hood design, although it is not entirely accepted or understood by laboratory designers. This hood design incorporates, according to the manufacturer, a "bi-stable vortex" to enhance its containment performance.

While the aforementioned strategies can result in energy savings, they fall short of the full potential, and have varying degrees of efficacy in ensuring safe operating conditions. Given the rising importance of electricity reliability and load management, it is also worth noting that these strategies may not diminish peak-power requirements.

New Approaches to Containment, Safety, and Energy Savings

Conventional hoods (and the above-mentioned energy efficiency strategies) rely on pulling supply air from the general laboratory space around the worker and research apparatus that may be located in the hood. Safety performance is susceptible to everyday activities in the lab, movement of people, opening and closing of doors, central air supply fluctuations, etc. Past efforts have not looked at the potential for re-conceptualizing and redesigning the hood to maintain or improve worker safety with lower airflows.

A new strategy for managing fume hood energy, the Berkeley Hood technique supplies air in front of the operator, while drawing only about 10 to 30 percent of the air from around the operator.[3] As a result, far lower flow-rates are necessary in order to contain pollutants and flow-rates remain virtually unaffected by adjustments to the sash opening. This supplied air creates a protective layer of fresh air free of contaminants. Even temporary mixing between air in the face of the fume hood and room air, which could result from pressure fluctuations in the laboratory, will keep contaminants contained within the hood.

[3] This generic concept was first tested in the "air vest" technology, invented at LBNL for use with large paint spray hoods (Gadgil et al. 1992) The vest supplies air in front of the operator of the hood, which creates a positive pressure field that prevents development of a wake, therefore ensuring clean air to the operator's breathing zone. Feustel mapped this concept to the problem of fume hoods (Feustel et al. 2001).

The Berkeley Hood uses a "push-pull" displacement airflow approach to contain fumes and move air through a hood (Figure 5). Displacement air “push” is introduced with supply vents near the top and bottom of the hood’s sash opening. Displacement air “pull” is provided by simultaneously exhausting air from the back and top of the hood. The low-velocity supply airflows create an “air divider” between an operator and a hood’s contents that separates and distributes airflow at the sash opening (unlike an air curtain approach that uses high-velocity airflow). When the face of a hood is protected by an air flow condition with low turbulent intensity, the need to exhaust large amounts of air from the hood is largely reduced. The air divider technology contains fumes simply, protects the operator, and delivers dramatic cost reductions in a facility’s construction and operation.

The Berkeley Hood must not be confused with the auxiliary air approach. There are fundamental and material differences, stemming from the fact that the Berkeley Hood does not utilize outside air, and that air is introduced from within the sash in a highly controlled fashion with far lower turbulence (and thus lower risk of contaminant spillage) than occurs with auxiliary hoods. In auxiliary-air hoods, turbulent airflows coming from above the worker in auxiliary-air systems increase mixing of incoming fresh air and contaminated air within a hood’s workspace.

An added attraction of the Berkeley Hood installation is that its incremental cost is expected to be less than that of VAV systems. Savings from downsized heating, ventilating, and air conditioning systems and less complicated controls would also be realized.

Barriers to Improving Performance and Energy Savings

There are material hurdles to widespread adoption of this new approach. The problem lies in various regulations that stipulate absolute airflow rates, rather than direct metrics of safety.

The ASHRAE Standard 110-1995 is the most widely used test method for evaluating a hood's containment performance in North America. This method recommends three types of tests but does not stipulate *performance* values that need to be attained by a fume hood. Aside from the ASHRAE method, the most commonly used indicator of hood capture and containment is hood face velocity. A commonly accepted value of 30.5 meters per minute (100 feet/minute, fpm) is widely applied. While this value has limited technical merit, its simplicity and pervasiveness presents the most significant barrier to widespread adoption of methods that result in lower air flow rates (even if safety is not compromised). Hoods using the above-mentioned push-pull technique provide containment of tracer gas and smoke per the ASHRAE 110 test but have an "equivalent" face velocity of approximately 9.1 to 15.2 meters per minute (30 to 50 fpm) (with the internal supply fans off). The actual velocity is much less as most of the air is introduced at the face.

In California, CAL/OSHA also requires a 30.5 meter per minute (100 fpm) face velocity for a laboratory fume hood (non-carcinogen) to be in compliance, limiting the use of the push-pull approach and potentially in other States that follow California's lead.

Other similar barriers can be found in a variety of standards. For example, the U.S. Environmental Protection Agency promulgates a standard used in their procurement procedures but is also adopted for use by others. The requirement for 30.5 meter-per-minute (100 fpm) face velocity is deeply ingrained through this industry and is a major market barrier to push-pull hoods.

Conclusions and Research Needs

Laboratory fume hoods are important energy end-use devices, with considerable untapped savings potential. However, existing approaches for improving performance and saving energy in fume hoods are complicated and costly to implement, and often do not address worker safety issues inherent in traditional fume hood design. Innovation is hampered by various barriers stemming from existing fume hood testing/rating procedures, entrenched industry practices, and ambiguous and often contradictory guidance on safe levels of airflow.

Improvements to hood designs—largely unchanged for many decades—have been identified. It is unfortunate (and ironic) that existing safety codes both impede improvements in energy efficiency as well as safety. Efforts are underway to improve this situation.

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Table 1. Fume Hood Energy Use Model

Country	Thailand	China	Germany	China	Malaysia	Norway	Singapore	Taiwan	Canada	Japan
City	Bangkok	Beijing	Berlin	Hong Kong	Kuala Lumpur	Oslo	Singapore	Taipei	Toronto	Tokyo
Electricity Price: avg. of com'l and ind'l tariff ($/kWh)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070
Electricity Demand Charge ($/kW-year)	120	120	120	120	120	120	120	120	120	120
Natural Gas Price ($/MBTU)	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50
Cooling & Air-handling Electricity										
Cooling ton-hours/CFM (55deg supply) [1]	52.01	13.06	3.99	34.85	52.80	1.13	56.12	32.19	4.95	17.52
Chiller energy (kWh/year)	65,013	16,325	4,988	43,563	66,000	1,413	70,150	40,238	6,188	21,900
Fan energy (kWh/year)	19,710	19,710	19,710	19,710	19,710	19,710	19,710	19,710	19,710	19,710
Total (kWh/year)	84,723	36,035	24,698	63,273	85,710	21,123	89,860	59,948	25,898	41,610
Total Power (kW/hood)										
Fan	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Chiller (assuming outside air cooled 40 degrees F)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Total kW	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Cooling and Air-handling Electricity Cost										
Electricity ($/year) [2]	5,931	2,522	1,729	4,429	6,000	1,479	6,290	4,196	1,813	2,913
Demand ($/year)	810	810	810	810	810	810	810	810	810	810
Total ($/year)	6,741	3,332	2,539	5,239	6,810	2,289	7,100	5,006	2,623	3,723
Heating Energy										
Supply Heating Energy (Therms/CFM, 55 deg) [1]	0.00	0.85	0.99	0.01	0.00	1.80	0.00	0.01	1.30	0.29
Supply at 55 deg. F (BTU, Load)	-	106,250,000	123,750,000	1,250,000	-	225,000,000	-	1,250,000	162,500,000	36,250,000
Reheat 10 deg (55 to 65F) (BTU)	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000
Total Load (BTU)	118,260,000	224,510,000	242,010,000	119,510,000	118,260,000	343,260,000	118,260,000	119,510,000	280,760,000	154,510,000
Energy (kWh) [3]	0	0	0	0	0	0	0	0	0	0
Energy (BTU, gas)	168,942,857	320,728,571	345,728,571	170,728,571	168,942,857	490,371,429	168,942,857	170,728,571	401,085,714	220,728,571
Heating Cost ($/year) [2]	1,098	2,085	2,247	1,110	1,098	3,187	1,098	1,110	2,607	1,435
Total Per-Hood Energy Cost ($/year)	7,839	5,417	4,786	6,349	7,908	5,476	8,198	6,116	5,230	5,157
Cost per cfm	6.27	4.33	3.83	5.08	6.33	4.38	6.56	4.89	4.18	4.13

System Assumptions

Hoods use 100% outside air, 24/7/365 operation; constant-volume system	30.47851265	Kjelgaard assumes 0.9W/CFM for supply only)
Hood Flow (six-foot nominal opening)	1250 CFM	Kjelgaard assumes a range of 0.45 to 1.4
Combined fan power (supply/exhaust) [4]	1.8 W/CFM	for a range of cooling plant types
Cooling plant efficiency [1]	1 kW/ton	
Heating system efficiency	70%	
Outside air is cooled or heated to 55deg. F supply temperature		BTU/year-CFM
Air is reheated at each zone for temperature control; Conservatisms: supply air often cooler, humidification energy not included in this analysis		= (0.018 BTU)(10deg F)(60min)(24h)(365days)
Reheat Energy (assume average delta-T is 10F: 55->65F)	94,608	MJ/year-cubic meter/minute
	3,525	

Sources:

1. Kjelgaard, J.M. 2001. Engineering Weather Data. McGraw-Hill. ISBN 0-07-137029-3
2. Energy Prices: (weighted according to 0.75 commercial and 0.25 industrial tariffs). Demand charges are LBNL estimates. For sources, see:
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3. Electric reheat is not widespread, but incurs a large energy penalty where used (e.g. nearly twice the fume hood's direct fan energy use in this case for Seattle)
4. Weale, J., P.H. Rumsey, D. Sartor, and L.E. Lee. 2002. "Laboratory Low-Pressure-Drop Design". ASHRAE Journal, vol. 44, no. 8, p. 38-42.
5. Based on conservative interpretation of field tries of the Berkeley Hood "push-pull" technology (Bell et al. 2002)

Table 1 (cont'd)

City	US - Anchorage AK	US - District of Columbia	US - Houston TX	US - Missoula MT	US - Miami, FL	US - Minneapolis, MN	New York, NY	US - Sacramento	US - Seattle
Electricity Price: avg. of com'l and ind'l tariff ($/kWh)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070
Electricity Demand Charge ($/kW-year)	120	120	120	120	120	120	120	120	120
Natural Gas Price ($/MBTU)	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50
Cooling & Air-handling Electricity									
Cooling ton-hours/CFM (55deg supply) [1]	0.71	10.83	25.45	3.03	34.55	6.83	8.10	6.38	2.49
Chiller energy (kWh/year)	888	13,538	31,813	3,788	43,188	8,538	10,125	7,975	3,113
Fan energy (kWh/year)	19,710	19,710	19,710	19,710	19,710	19,710	19,710	19,710	19,710
Total (kWh/year)	20,598	33,248	51,523	23,498	62,898	28,248	29,835	27,685	22,823
Total Power (kW/hood)									
Fan	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Chiller (assuming outside air cooled 40 degrees F)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Total kW	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Cooling and Air-handling Electricity Cost									
Electricity ($/year) [2]	1,442	2,327	3,607	1,645	4,403	1,977	2,088	1,938	1,598
Demand ($/year)	810	810	810	810	810	810	810	810	810
Total ($/year)	2,252	3,137	4,417	2,455	5,213	2,787	2,898	2,748	2,408
Heating Energy									
Supply Heating Energy (Therms/CFM, 55 deg) [1]	1.81	0.76	0.21	1.39	0.01	1.46	0.77	0.33	0.61
Supply at 55 deg. F (BTU, Load)	226,250,000	95,000,000	26,250,000	173,750,000	1,250,000	182,500,000	96,250,000	41,250,000	76,250,000
Reheat 10 deg (55 to 65F) (BTU)	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000	118,260,000
Total Load (BTU)	344,510,000	213,260,000	144,510,000	292,010,000	119,510,000	300,760,000	214,510,000	159,510,000	194,510,000
Energy (kWh) [3]	0	0	0	0	0	0	0	0	34,650
Energy (BTU, gas)	492,157,143	304,657,143	206,442,857	417,157,143	170,728,571	429,657,143	306,442,857	227,871,429	277,871,429
Heating Cost ($/year) [2]	3,199	1,980	1,342	2,712	1,110	2,793	1,992	1,481	1,806
Total Per-Hood Energy Cost ($/year)	5,451	5,118	5,758	5,166	6,323	5,580	4,890	4,229	4,214
Cost per cfm	4.36	4.09	4.61	4.13	5.06	4.46	3.91	3.38	3.37

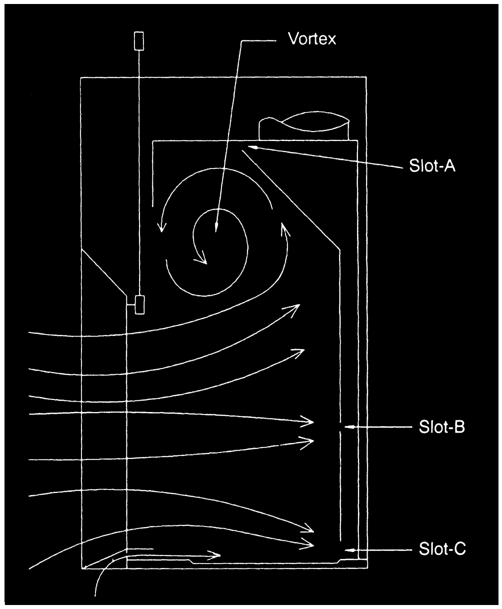
Table 2. Fume Hood Energy Savings Potentials

	United States*	California
MACRO-SCALE ENERGY USE		
Number of Hoods	750,000	85,000
Total Electricity (GWh/year)	26,183	2,353
Total Peak Power (MW)	5,063	574
Total Natural Gas (Trillion BTUs/year)	194	19
Total Energy Cost ($ Million/year)	3,673	359
MACRO-SCALE ENERGY SAVINGS		
Per-hood energy savings**	50%	50%
Maximum potential market penetration	75%	75%
Electricity ($M/year)	687	62
Demand ($M/year)	228	26
Natural Gas ($M/year)	462	47
Total Energy Savings ($ Million/year)	1,377	135
Total Electricity Savings (GWh/year)	9,818	882
Total peak power savings (MW)	1,898	215
Total heating fuel savings (TBTU)	73	7

* US Average is modeled as average of Los Angeles, Chicago, Miami, and New York

** conservative given that R&D goal is to reduce air flow 75% (to 25%) and theoretical fan savings is a cubed function (a 50% reduction in flow would result in over an 80% savings in fan HP). This conservatism balances existing use of VAV hoods, and potential that fume hood exhaust may drop bellow general lab exhaust requirements.

Figure 1. Typical fume hood cross-section, application and relation to HVAC system (TekAir 2003; Saunders (1993).



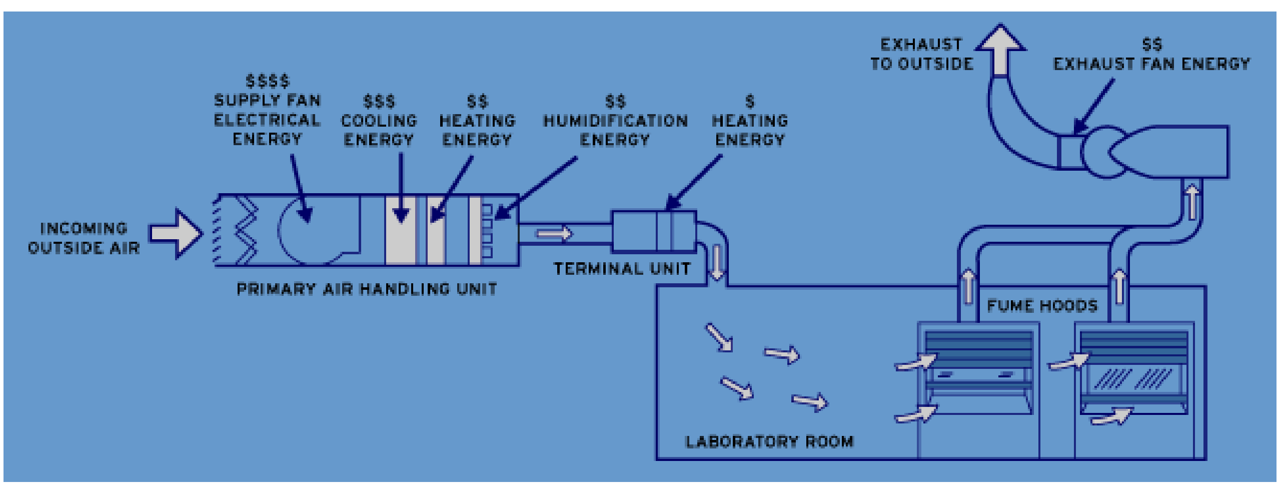


Figure 2. Fume hood energy use in California, by sub-climate. Using California average energy prices.

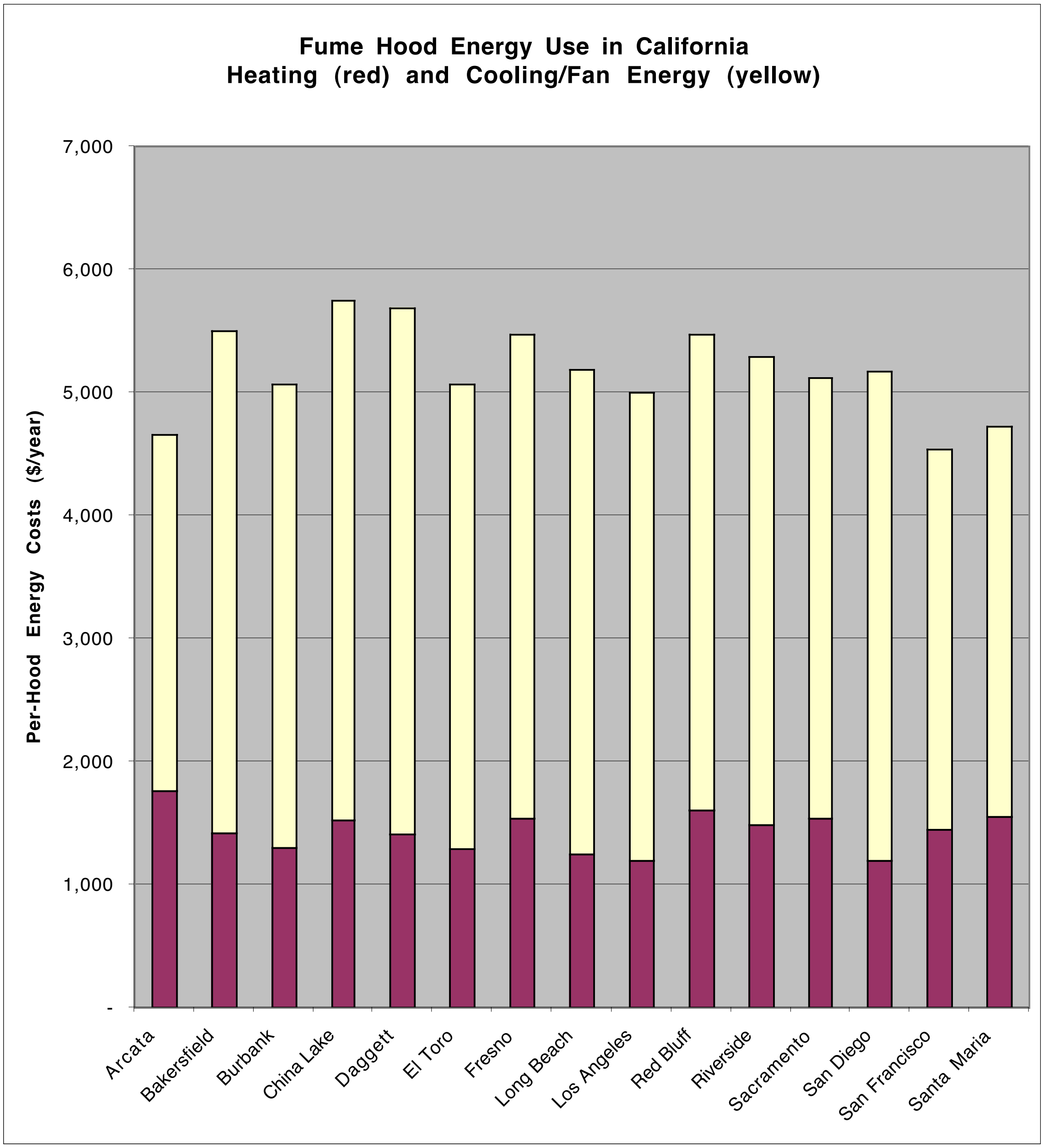
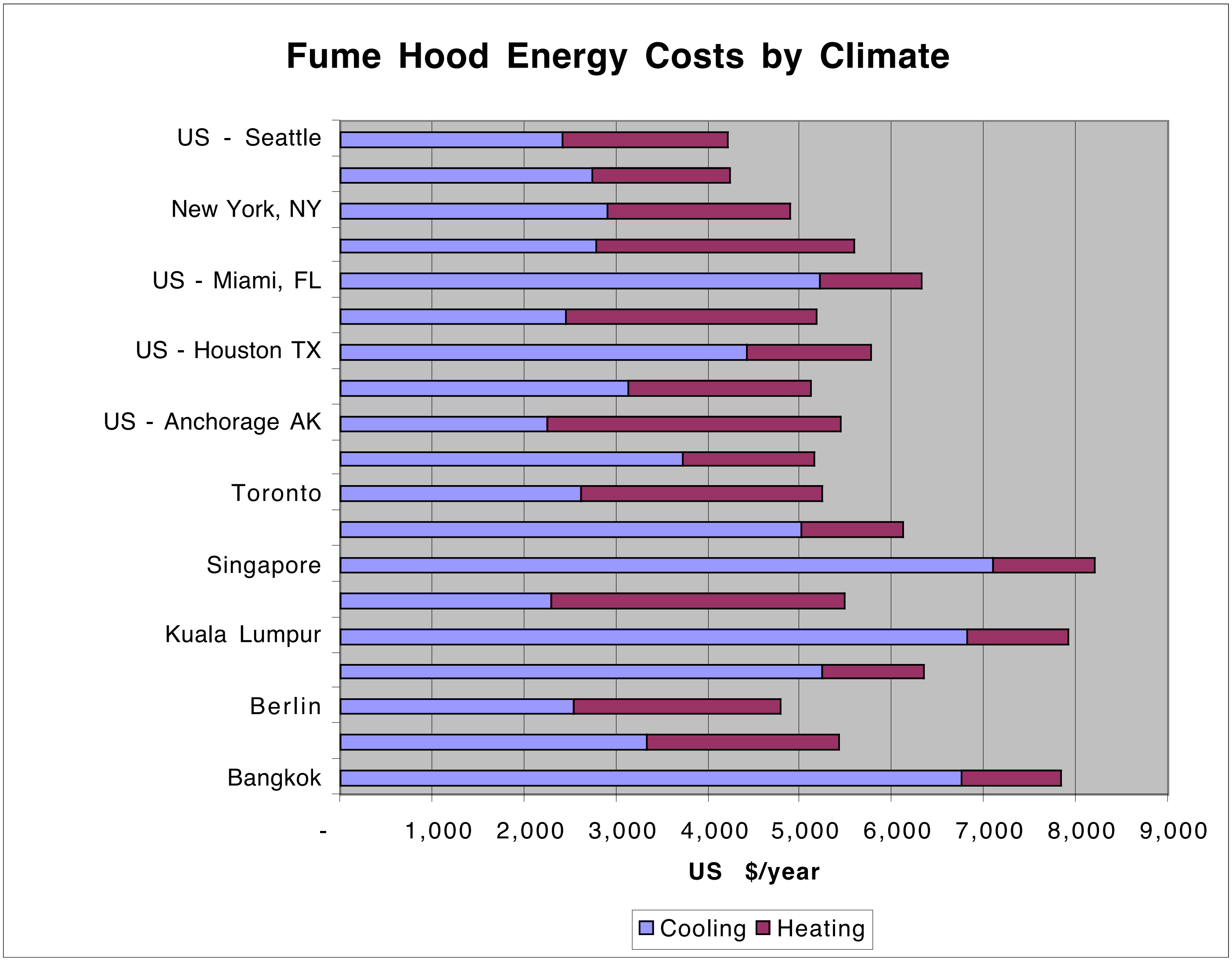


Figure 3. Variability in fume hood energy costs across the US and Asia. Xx reinsert



Beijing

Figure 4. Assumes fuel used for heating and electricity for cooling. Energy prices normalized to \$0.07/kWh and \$6.85/GJ). Engineering assumptions as in Table 1.

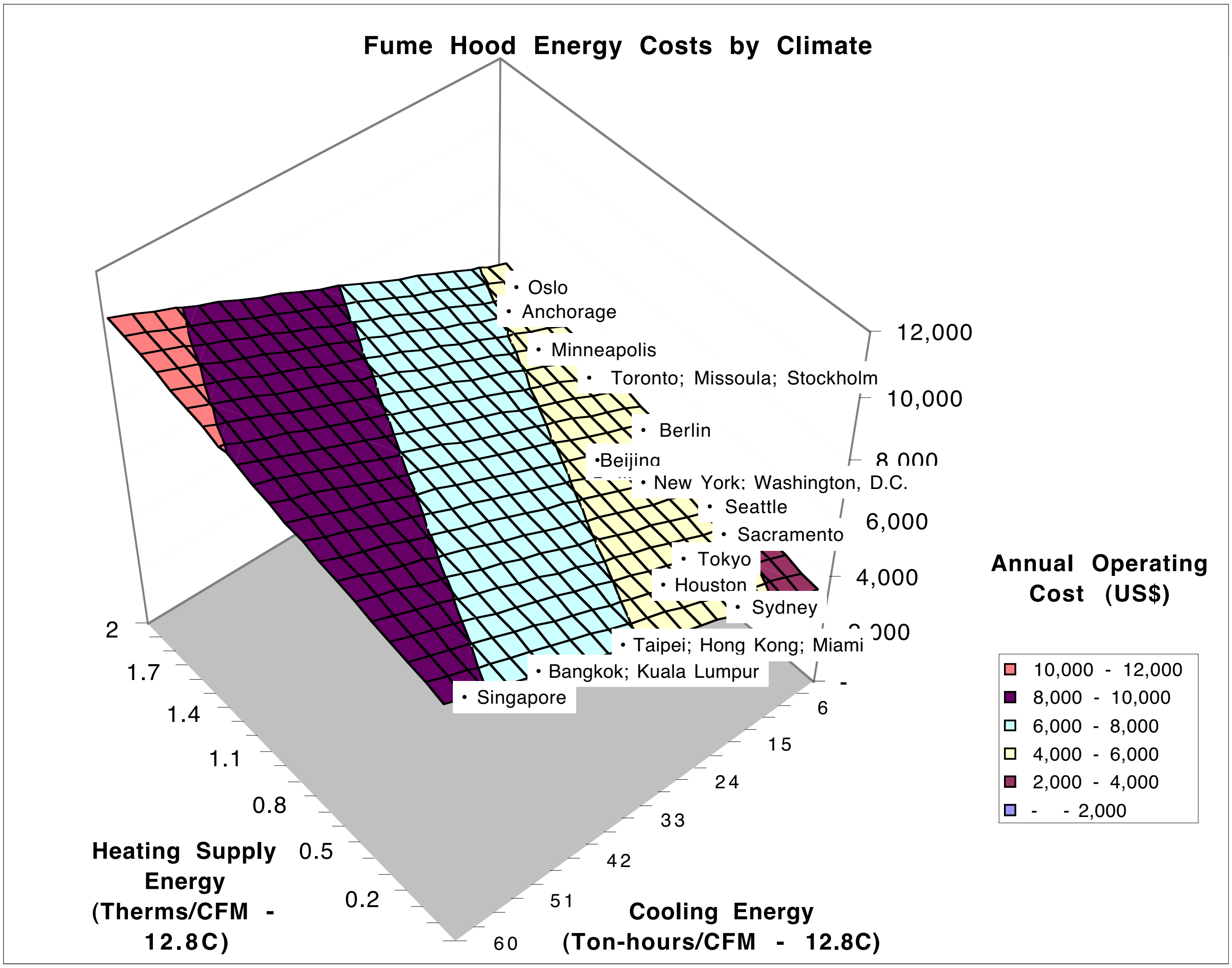


Figure 5. Cross section and front view of push-pull fume hood technology ("Berkeley Hood") (Bell et al. 2002).